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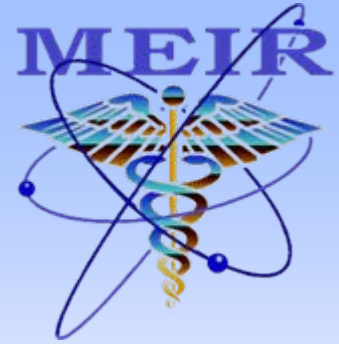
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Fundamentals of Radiation Physics



Objectives

- **Define ionizing radiation**
- **Describe sources of ionizing radiation**
- **Describe interaction of ionizing radiation with matter at microscopic level**
- **Describe interaction of ionizing radiation with matter at macroscopic level**



Categories of Ionizing Radiation

- Directly ionizing
 - Charged particles
 - e^- e^+ p^+ α^{++} π^- heavy nuclei
 - $\alpha^{++} = {}^4\text{He}^{+2}$
- Indirectly ionizing
 - Photons
 - $E = h\nu$ (Greek letter nu = frequency)
 - γ rays = photons of nuclear origin
 - Neutrons



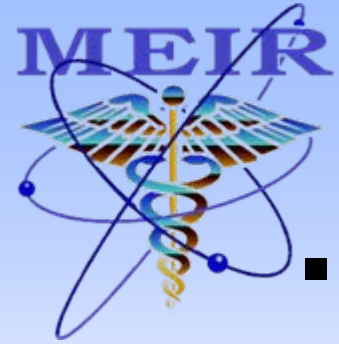
Sources of Ionizing Radiation

- Electrically generated
 - Charged particle accelerators
 - Van de Graaff generator, cyclotron
linear accelerator, synchrotron, betatron,
microtron, rhodotron
- Radionuclides
 - Atom with an unstable nucleus
 - Naturally occurring
 - Man-made (induced)



Basic Nuclear Physics

- Nuclei have different energy states
 - Ground state
 - Metastable or isomeric nuclear states
 - Often $> 10^{-12}$ sec or on the order of hours
 - Excited nuclear states
 - Usually $< 10^{-12}$ sec
- Terminology
 - Isotopes: same Z (atomic number)
 - Isobars: same A (atomic mass)
 - Isotones: same N (number of neutrons)



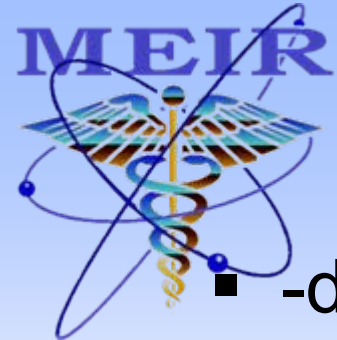
Nuclear Processes

- β^- decay
 - $n \rightarrow p^+ + e^- + \text{antineutrino} + \text{KE}$
- β^-, γ decay
 - $n \rightarrow p^+ + e^- + \text{antineutrino} + \text{KE}$
followed by γ release
- β^+ decay
 - $p^+ \rightarrow n + e^+ + \text{neutrino} + \text{KE}$
followed by e^+/e^- annihilation
- β^+, γ decay
 - $p^+ \rightarrow n + e^+ + \text{neutrino} + \text{KE}$
followed by γ release and e^+/e^- annihilation



More Nuclear Processes

- Electron capture
 - $p^+ + e^- \rightarrow n + \text{neutrino} + \text{KE}$
then characteristic x-rays or Auger electrons
- Electron capture, γ
 - $p^+ + e^- \rightarrow n + \text{neutrino} + \text{KE}$
followed by γ release
then characteristic x-rays or Auger electrons
- α decay
- α decay, γ
 - followed by γ release



Basic Mathematical Formulation

- $-dN/dt = \lambda N$ (λ = decay constant)
- $N(t)/N_0 = e^{-\lambda t}$
- $N(t) = N_0 e^{-\lambda t}$
- Activity is defined as $-dN/dt$
- $A(t) = A_0 e^{-\lambda t}$
- $\ln 2 = \lambda T_{1/2}$ ($T_{1/2}$ = half life)
- $0.693 = \lambda T_{1/2}$
- $\lambda = 0.693 / T_{1/2}$
- Often useful to use e^{-x} where $x = (0.693 / T_{1/2})t$
- For small values of λt : $e^{-\lambda t} \approx 1 - \lambda t$
- Average lifetime: $\tau = 1/\lambda = 1.44 T_{1/2}$



International System of Units (SI) and Radionuclide Activity & Decay

- SI unit of activity is becquerel (Bq)
- $1 \text{ Bq} = 1 \text{ sec}^{-1}$
- Describes rate of decay as number/sec
- Thus $1 \text{ Bq} = 1$ “disintegration” per sec (dps)
- Another unit of activity is the Curie (non-SI)
- $1 \text{ Ci} = 3.7 \times 10^{10} \text{ sec}^{-1}$ or $3.7 \times 10^{10} \text{ Bq}$
- Therefore $1 \text{ Bq} = 2.7 \times 10^{-11} \text{ Ci}$



Specific Activity

- Carrier: stable isotopes of same element in the sample are called carriers
- Specific activity defined as:
radioisotope activity/total mass of element present
- Units of specific activity (non-SI): Ci/g
- $m = \text{activity/specific activity}$
- Highest possible specific activity is referred to as the carrier free specific activity



Production of Radionuclides

- Nuclear reactor
 - Neutron activation
 - Not carrier free; tend to decay by β^- emission
- Particle accelerator
 - Cyclotron often used to add positive charge
 - Carrier free; tend to decay by β^+ emission
- Photonuclear
 - Low yield
 - Not carrier free; tend to decay by β^+ emission



SI Units - Matter - Energy

- Fundamental units of nature (MKS-A)
length - mass - time - ampere
meter - kilogram - second - ampere
- Other supplementary units
temperature (kelvin: K)
amount of substance (mole: mol)
luminous intensity (candela: cd)
- All other units are derived
eg: electrical potential (volt)
 $1 \text{ V} = 1 \text{ m}^2 \text{ kg s}^{-3} \text{ A}^{-1}$



SI Units - Matter - Energy

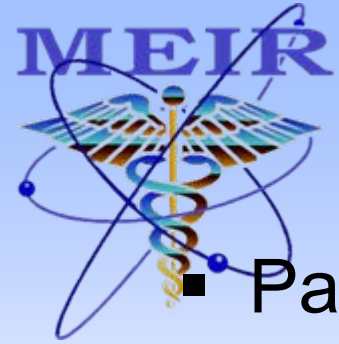
- Matter: fundamental property in universe
- Energy: fundamental component of nature
- Energy = ability to do work
- Recall: work = force x distance (newton x meter)
- Energy can be expressed in several ways
- SI unit of energy is joule (J)
- $1 \text{ J} = 1 \text{ m}^2 \text{ kg s}^{-2}$
- Total energy = kinetic energy + potential energy
- Consider 1 e- accelerated across an electrical potential of 1 volt acquires a KE of 1 eV
- $1 \text{ eV} = 1.6022 \times 10^{-19} \text{ J}$



SI Units - Matter - Energy

- Matter represents a form of potential energy
- Mass increases as KE approaches speed of light
- An object at rest has its own rest mass energy

	$m_0 c^2$	m_{e^-}
e^-	0.511 MeV	1
μ^-	106 MeV	207
π^-	140 MeV	273
p^+	938.26 MeV	1836
n	939.55 MeV	1839



Fundamental Quantities

- Particle fluence

$$\Phi = dN/da$$

- Energy fluence

$$\Psi = dE/da$$

- Exposure (roentgen - R)

$$X = dQ/dm$$

where dQ is the sum of the electrical charges of one sign on all the ions produced in air when all the electrons liberated by photons in a volume of air of mass dm are completely stopped in air

$$1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$$



Principles of Attenuation

- Attenuation = reduction in the number of particles in a radiation beam as it passes through an absorber
- Can occur as a single event or series of events
- Energy loss by an extended series of energy transfer events predominates for charged particle beams
- The concept of range and path length mostly appropriate for charged particle beams
- Energy loss by indirectly ionizing radiation beams can occur in a single event or gradual degradation
- Mean free range & half value thickness of absorber more meaningful for indirectly ionizing radiation



More on Attenuation

- Involves the processes of absorption and scatter
- Based on the concept of a reaction cross section
- Cross section = probability per target per unit area
- Probabilities of independent processes additive
- Attenuation terminology different for charged particle and indirectly ionizing radiation beams
- Charged particle beams scatter elastically
- Energy loss related mostly to inelastic processes
- Linear attenuation coefficient best describes attenuation for indirectly ionizing radiation beams



Energy Loss by Charged Particles

- Predominantly occurs through inelastic collisions with atomic electrons and nuclei
- Involves coulomb force and strong force
- Energy loss per unit length called stopping power
- Depends on particle, its KE, and Z of medium
- KE often symbolized by T
- Stopping power: collisional and radiative
$$dT/dx = dT/dx_C + dT/dx_R$$
- Mass stopping power
$$dT/pdx = dT/pdx_C + dT/pdx_R$$



Photon Attenuation Processes

- Atomic photoelectric effect

$${}_a\tau \leftrightarrow Z^4/(h\nu)^3 \text{ x-section/atom for } h\nu \leq 0.1 \text{ MeV}$$

- Compton scattering

$${}_e\sigma \leftrightarrow Z \text{ x-sec/electron} \quad \& \quad {}_a\sigma = Z {}_e\sigma \text{ x-sec/atom}$$

Compton effect dependent on atomic e^- density

Atomic e^- density mostly constant except for H

- Atomic pair production

$${}_a\kappa \leftrightarrow Z^2 \text{ cross section/atom}$$

- Rayleigh scattering

$${}_a\sigma_R \leftrightarrow (Z/h\nu)^2 \text{ cross section/atom}$$



Photon Attenuation

- Total linear attenuation coefficient
$$\mu = \tau + \sigma + \kappa + \sigma_R$$
- Total mass attenuation coefficient
$$\mu/\rho = \tau/\rho + \sigma/\rho + \kappa/\rho + \sigma_R/\rho$$
- Under ideal narrow beam conditions
$$N(x) = N_0 e^{-\mu x}$$
 (similar to radioactive decay eqn.)
- Under less ideal conditions (broad beam conditions)
$$N(x) = N_0 e^{-\mu' x}$$

where μ' = effective total linear attenuation coefficient



Photon Energy Transfer

- Photons transfer energy by generating secondary charged particles
- Almost all charged secondary particles are e^-
- Total energy transfer coefficient

$$\mu_{tr} = \tau_{tr} + \sigma_{tr} + \kappa_{tr} + (\gamma, p^+)_{tr} + (\gamma, n)_{tr}$$

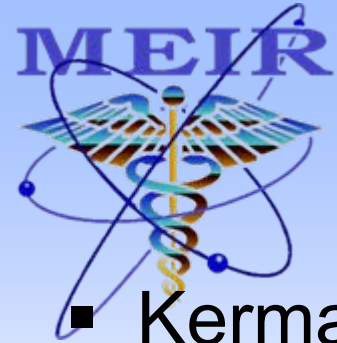
- Total mass energy transfer coefficient

$$\mu_{tr}/\rho = \tau_{tr}/\rho + \sigma_{tr}/\rho + \kappa_{tr}/\rho + (\gamma, p^+)_{tr}/\rho + (\gamma, n)_{tr}/\rho$$



Photon Energy Absorption

- Mass energy absorption coefficient
$$\mu_{\text{en}}/\rho = (\mu_{\text{tr}}/\rho)(1 - g)$$
where g = fraction lost to radiative interactions
 g increases gradually with increasing Z or $h\nu$
- Energy absorbed per unit volume correlates the amount of radiation with the effects of radiation
- Energy deposited per unit length along the track of radiation important and correlates to effects
- Duration of time associated with the delivery of radiation especially important in living systems
(Above subjects covered shortly or in next lecture)



Kerma and Exposure

- Kerma = kinetic energy relaxed in matter (K)
- $K = K_C + K_R$
- Energy required to produce a unit charge in air
 $(W/e)_{AIR} = 33.97 \text{ J/C}$
- Exposure (X) is ionization equivalent of K_C in air
- Equivalence valid only for photon energies $< 3 \text{ MeV}$
- $(K_C)_{AIR} = X(W/e)_{AIR}$
- SI units: $X(W/e)_{AIR} = (\text{C/kg})(\text{J/C}) = \text{J/kg}$
- Energy per unit mass $\leftrightarrow \text{J/kg}$
- Roentgen: $1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$
- $1 \text{ C/kg} = 3876 \text{ R}$



Kerma and Dose

- $K = K_C + K_R$
- $K = dE_{tr}/dm$
- $K = E_{tr} \Phi(\mu/\rho) = \Psi(\mu_{tr}/\rho)$
- $K_C = \Psi(\mu_{en}/\rho)$
- SI unit of dose (D) is the Gray (Gy)
- $1 \text{ Gy} = 1 \text{ J/kg}$ ($1 \text{ rad} = 1 \times 10^{-2} \text{ J/kg} = 100 \text{ cGy}$)
- $D = K_C$ under conditions of CPE
- Charged particle equilibrium is an important and necessary condition for D at the macroscopic level



Neutrons

- Characterized by their kinetic energy T
 - Cold neutrons: $5 \times 10^{-5} \text{ eV} \leq T < 0.025 \text{ eV}$
 - Thermal neutrons: $T = 0.025 \text{ eV}$ at 293° K
 - Epithermal neutrons: $0.025 \text{ eV} \leq T < 1 \text{ eV}$
 - Slow neutrons: $1 \text{ eV} \leq T < 1 \text{ keV}$
 - Intermediate neutrons: $1 \text{ keV} \leq T < 0.5 \text{ MeV}$
 - Fast neutrons: $0.5 \text{ MeV} \leq T < 10 \text{ MeV}$
 - High energy neutrons: $10 \text{ MeV} \leq T$
- Neutron beams essentially always occur as mixed photon/neutron beams



Neutrons

- Decay in free space with $T_{1/2} = 10.6$ min according to
$$n \rightarrow p^+ + e^- + \text{antineutrino}$$
- Reacts with other particles predominantly by the strong nuclear force at a range of 10^{-14} m
- Interactions produce elastic neutrons, γ photons inelastic neutrons, recoil atoms (nuclei), & fragments
- Neutron kerma $K = \Phi F_n$ with F_n = neutron kerma factor
- Neutron dose $D = K = \Phi F_n$ under conditions of CPE
- Dose effect from neutrons enhanced in living systems



Linear Energy Transfer (LET)

- Recall collisional and radiative stopping power

$$dT/dx = dT/dx_C + dT/dx_R$$

- LET equates to a restricted collisional stopping power with energy transfers \leq a specified value of Δ
- $L_\Delta = (-dT/dx)_C$ with $E \leq \Delta$

250 kV_p x-rays: LET = 2 keV/ μ m

^{60}Co γ rays: LET = 0.3 keV/ μ m

6 to 50 MeV e^- : LET \approx 0.2 keV/ μ m

14 MeV n: LET = 12 keV/ μ m

> 100 MeV p^+ : LET = 0.5 keV/ μ m \rightarrow 100 keV/ μ m

50 MeV π^- : LET = 0.3 keV/ μ m \rightarrow 100 keV/ μ m



Sievert – SI Unit of Dose Equivalent

- Sievert: $H = DQN$
 - D = absorbed dose (Gy)
 - Q = quality factor
 - N = product of all other dose-modifying factors
eg: spatial dose distribution or rate of delivery
- $1 \text{ Sv} = 1 \text{ J/kg}$ ($1 \text{ rem} = 1 \times 10^{-2} \text{ J/kg} = 100 \text{ cSv}$)
 - 250 kV_p x-rays: $Q = 1$
 - ^{60}Co γ rays: $Q = 1$
 - 6 to 50 MeV e^- : $Q = 1$
 - 14 MeV n : $Q = 10$ if $\geq 10 \text{ keV}$ & $Q = 3$ if $< 10 \text{ keV}$
 - $> 100 \text{ MeV } p^+$: $Q = 1$ to > 10 as a function of keV
 - 50 MeV π^- : $Q = 1$ to > 10 as a function of keV



Thank you for your attention

- Questions
- Comments
- Discussion

